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Biomass production in the Central Great Plains USA under various coppice regimes

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Abstract

This paper presents the results of numerous short-rotation coppicing studies with nine fast-growing hardwood tree species grown in the central plains states of the United States. The objective was to compare biomass production of various tree species planted at different densities, coppiced at several intervals, and the longevity of succeeding harvests. Survival, growth, and yield were evaluated. Plant spacing ranged from 0.3 × 0.3 m to 2.6 × 2.6 m. Above-ground dormant-season coppice weight and survival on small research plots with one- to five-year coppice cutting cycles were determined. Annual yield of 4–17 oven-dry weight $\mathrm{Mg\,ha^{-1}}$ for black locust, boxelder, catalpa, cottonwood, honey locust, silver maple, and Siberian elm resulted after several cuts. Survival of cottonwood was about 12% over a 20-year period. Stump sprouting was prolific in silver maple (6.1 per tree); nearly twice as many as the other species compared. Multiple harvests are feasible for many of the broadleafed species evaluated in this study. Survival decreases dramatically at the very close (less than 1 m) spacings. Tonnage remains high for cutting cycles of one, two, or five years. At least three harvests appear feasible. Considering high establishment costs along with survival results conventional spacing distances of about 2 m is suggested for high biomass production especially if plantation longevity of 10 or more years is desired.

Keywords: Biomass production; Coppice; Cutting cycles; Short-rotation forestry; SRIC; Spacing trials

1. Introduction

Growing woody plants under the short-rotation, intensive-culture (SRIC) system is an appealing concept for producing biomass in a minimal period of time. Borrowing heavily from practices used in agriculture, SRIC relies on fast-growing hardwood tree species, close planting densities, short-rotation harvests, improved genetic stock, fertile sites, and coppice regrowth as components of this approach. Regenerating succeeding stands from stump sprouts at little additional cost makes this an appealing management procedure Geyer et al. [1] because stand establishment is cited as the greatest cost in the SRIC concept [2]. An important aspect of the establishment and management of a coppice plantation is the spacing, which is closely related to the harvesting cycle; furthermore the season of harvesting, and the method of harvesting leaving stumps or stools of different sizes and heights, will also have a strong influence on the resprouting and sustainability of the plants [3]. Field trials with *Eucalyptus* in New Zealand with short three-year cutting cycles have found that coppice yields were not decreased and survival was high [4]. Commercial short-rotation *Eucalyptus* coppice crops supply a bioenergy conversion plant in central North Island of New Zealand [5]. Although total costs per hectare are higher than those for conventional forest-management systems due to the high number of trees planted, the close tree-spacing and management intensity can significantly increase biomass production by quickly using the land that would have been unoccupied between normally spaced trees. Many studies in the past have reported early results of the SRIC system showing high biomass yields [2,6,7] and at competitive prices of delivered wood chips from conventional forest sources [2].

Several years of research have been completed in the evaluation of woody biomass production using the short-rotation concept on representative sites in the Central

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Great Plains of the United States [7–9]. Whether or not to use coppicing schemes, tree planting density (number of plants), length of cutting cycle, and number of harvests are important in determining the validity of SRIC for fiber production. The objective of this report is to compare biomass yield of several tree species as related to various planting densities, cutting cycles, and longevity. High-density, close-spacing, and conventional-spacing trials, which were cut numerous times to evaluate repeated coppice growth, were evaluated.

2. Materials and methods

All studies were planted at the same site which was a flat, alluvial, old-field site near Manhattan, Kansas (39.62°N 96.62°W) at 366 m above sea level and was cultivated prior to planting. Precipitation averages about 82 cm per year, with 75% coming during the growing season. The soil was classified in the Eudora silt loam series (coarse-silty, mixed, mesic, Fluventic Hapudolls) and consisted of 25 cm of silt loam soils underlain by very fine sandy loam. Soil characteristics are pH of 7.5, 2.0% organic matter, 146 kg available phosphorous (P), and 560 kg exchangeable potassium (K) per hectare. Several tree species of unselected genetic material were planted as one-year-old, bare-root seedlings in the spring over several years. Statistical designs in the four field studies were factorial.

Two high-density (wood-grass) studies were planted. The first with only silver maple (*Acer saccharinum L.*) in 1968 at 0.3 × 0.3, 0.45 × 0.45, or 0.6 × 0.6 m distances (49, 25, 16 trees per plot) on 1.8 × 1.8 m plots with six replications. After three years of seedling growth, the trees were cut annually.

A second study was established in 1985 with five species (black locust, *Robinia pseudoacacia L.*; cottonwood, *Populus deltoides* Bartr.; honey locust, *Gleditsia triacanthos L.*; silver maple; and Siberian elm, *Ulmus pumila L.*) at 0.3 × 0.3 m spacing (260 trees per plot) on 7.3 × 7.3 m plots, with three replications, and trees were cut annually for six years. The interior 100 trees were sampled.

A close-spacing study was planted in 1971 with nine tree species (boxelder, *Acer negundo* L.; catalpa, *Catalpa speciosa* Warder; cottonwood, field and clonal; European black alder (unknown origin), *Alnus glutinosa* L. Gaertn.; silver maple; sandbar willow, *Salix exigua* Nutt.; sycamore, *Platanus occidentalis* L.). Most of the seedlings came from Midwestern USA nurseries. The geographic seed source of silver maple and sycamore was Missouri, cottonwood from Missouri and Nebraska (Siouxland—a male cottonwood clone), sandbar willow from central Kansas, boxelder from Tennessee, and European black alder from Illinois. One-year-old seedlings were planted in rows 1.2 m apart and at spacings of 0.3, 0.6, and 1.2 m within the row. Single species plots consisted of 30 rows, with 10 rows blocked for each of the three spacings. One-hundredth hectare plots with one-row borders were thus set up for each spacing, and randomly placed with 370, 190, or 100 trees per plot spacing, respectively, and trees were cut every two years. Specific details of soil/site and management characteristics are reported in Geyer [8].

The field design was a two-way factorial (species by spacing) with one replication, and the species means were evaluated by multiple comparison-test rankings. Spacing for each species was not analyzed. The three spacing treatment subplots were used to analyze spacing and species differences for all species combined. Species were established as whole plots and spacings were subplots of the whole plots.

A final conventional-spacing-study was conducted in 1980 with three tree species (silver maple, cottonwood, and black locust); trees were cut at five-year intervals and evaluated over four cutting cycles. A Nelder circular-plot design [10] containing 30 spokes with seven rings was used, and was replicated nine times with 210 trees in each circle (Figs. 1 and 2). Three tree species were planted per circle, with each species in 10-spoke clusters with average spacing distances ranging from 1.2 × 1.2 to 2.6 × 2.6 m. Species comparisons were made by averaging data for the inner five rings having an average spacing of 1.8 × 1.8 m. Because spacings were not randomized, conclusions about the statistical analysis are limited only to species differences.

Survival, total height, number of stump sprouts, ground-line diameters, and total-tree oven-dry weight (Mg ha^{-1}) were measured annually in studies 1 and 2, biennially in study 3, and at five-year intervals in study 4 during the dormant season. Plot weights were taken in all but the large-tree, conventional-spacing study 4 (1980) in which plot weights were determined from destructive sampling for

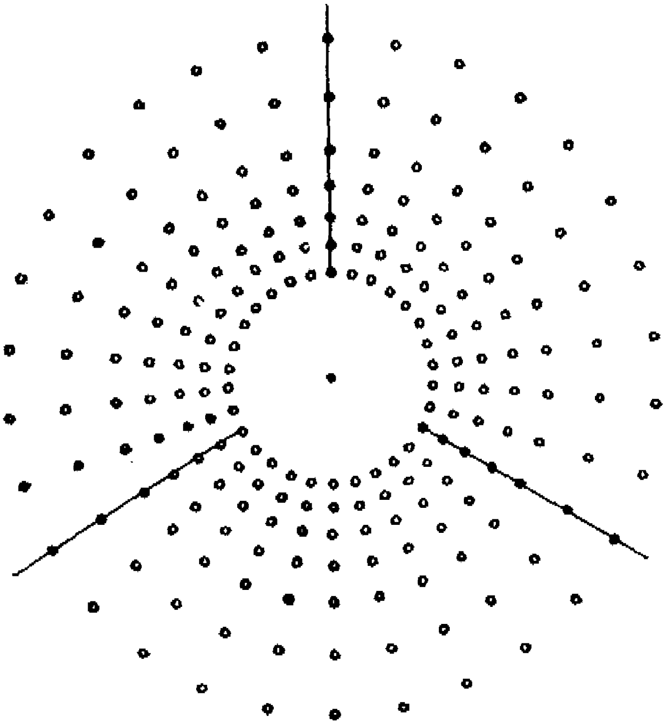

Fig. 1. Nelder design for variable stand density.

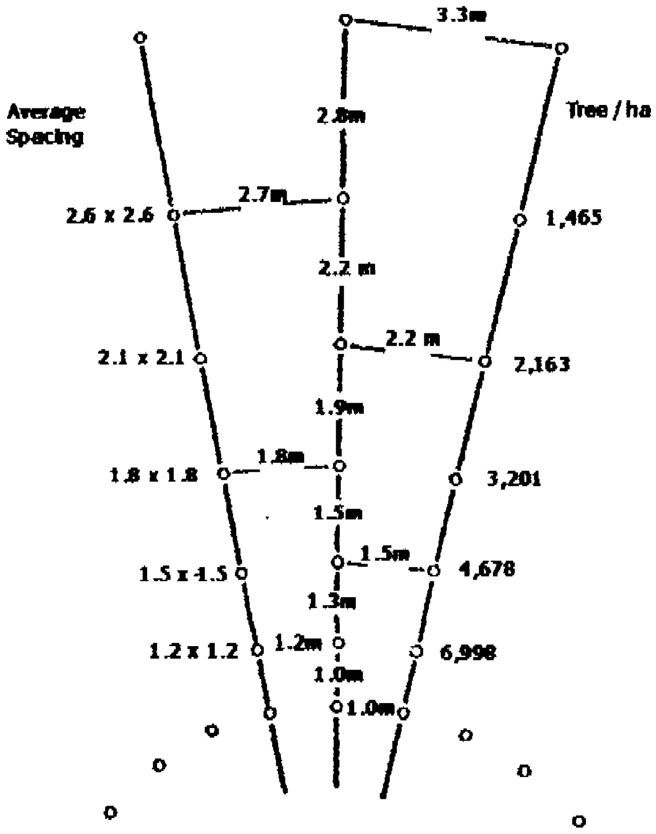

Fig. 2. Dimensions of three adjacent spokes.

each of the species, and prediction curves using ground-line stump diameter and total height were generated [8] for biomass yield. The maximum size–density relationship, a general principal of plant population biology [3], when used in pure even-aged stands was determined using the $\frac{3}{2}$ Law of Self-Thinning [11], with the logarithm of mean tree weight over the logarithm of surviving density to evaluate crowding. Data were analyzed using analysis of variance at $P = <0.05$ [12]. Spacing and species or species only were separated using Duncan's multiple range test—study 1: spacing only, study 2: species only, study 3: spacing and species, and study 4: species only.

3. Results and discussion

3.1. High-density trials (wood-grass)

In the 1968 study, very close spacing initially decreased significantly silver maple survival and increased yield (Table 1). Survival was least at the closer spacing and decreased with successive harvests. After eight years, survival ranged from 29% to 50%. First rotation annual yields, from the closest to the widest spacing, averaged nearly 8.7, 5.8, and 4.0 dry tonne (Mg ha^{-1}), respectively, but showed no significant difference (12.8, 10.8, and 14.8 tonne) after eight years. Coppice growth varied by year and, after five harvest cuts, yield was increased by 234% (all three spacings combined). Steinbeck and Nwoboshi [13] found spacing did not affect rootstock biomass production in rotations greater than two years with *Platanus occidentalis* L. in Georgia. Similar results were found with willow species in Sweden [14]. Densely spaced stands exhibited higher production than wider spacings during the first harvest under short-rotation periods and 0.5–1 m spacing. Short cycles spacing in later harvests did not affect biomass yields.

The second study (1985) also showed that survival decreased significantly to about 22% after six annual cuts for black locust, cottonwood, and silver maple, but remained high (about 82%) for honey locust and Siberian elm. Black locust initially gave the greatest yield (Table 1), but, after many annual harvests, the coppice yields for Siberian elm were 37–57% greater than the other species. Similar studies are being conducted in central Spain using Siberian elm [15]. Comparisons between the first harvest yield and subsequent coppice yield showed tonnage increased for boxelder, cottonwood, European black alder, and silver maple for three harvest cycles. Improved genetic stock may produce higher yield than found with nursery grown material used in this study.

During years of reduced precipitation, tonnage decreased in this study but improved substantially as precipitation increased later (see Table 1, study 2, fifth harvest period in 1989). Below average precipitation was experienced in the winter of 1988 and through the end of the growing season in 1989 (25.4 vs normal 50.8 cm).

Similar results to my high-density studies 1 and 3 were found with *Populus* grown in the Pacific Northwest [16,17] during the first two years of closely planted (0.5 × 0.5 to 1.5 × 1.5 m) trees. The closer spacing utilized the gaps in these early years which are quickly filled. In Sweden, willows responded similarly in the early stages of one- to three-year cutting cycles with spacings of 0.5 × 0.5, 0.6 × 0.6, 0.7 × 0.7 or 1 × 1 m [14]. In Georgia [4], spacing did not affect biomass production of sycamore grown for longer cutting cycles (>3 years) over a nine-year period. Thus growing trees at high densities is questionable as higher establishment costs have been reported [12], the number of plants thin out quickly, and biomass potential is nearly the same for all spacings.

3.2. Close-spacing trials

Survival for all species was 96% at the time of the first two-year seedling harvest, but dropped markedly after three cuts. Catalpa was planted at only the 1.2 × 1.2 m spacing and was discontinued after three cuts due to operational reasons. Siouxland cottonwood, sandhill willow, and sycamore were abandoned after three cuts because mortality was exceedingly high. Survival of the remaining four species after the third and fourth coppice cuts was 59% and 51%, respectively (Table 2). Survival was much greater (68%) at the wider 1.2 × 1.2 m spacing. Survival differed significantly (1%) by species—boxelder

Table 1
Annual oven-dry yield and survival in high-density trials with one- or two-year cutting cycles (studies 1 and 2)

Year	Species	Space	Harvest period[a]						Fifth or sixth harvest	
			First	Second	Third	Fourth	Fifth	Sixth	Yield[a]	Survival
		(m)	(Mg ha^{-1})	(Percentage of first cut yield)					(Mg ha^{-1})	(%)
Study 1—annual cut after third year										
1968 test	Silver maple	0.3 × 0.3	8.7a	64	103	83	147	–	12.8a	29b
		0.45 × 0.45	5.8b	59	143	109	186	–	10.8a	28b
		0.6 × 0.6	4.0b	130	270	190	370	–	14.8a	50a
Study 2—annual cuts										
1985 test	Black locust	0.3 × 0.3	6.5a	180	180	83	31	108	7.0b	17b
	Cottonwood	0.3 × 0.3	4.3b	193	235	88	67	105	4.5c	15b
	Honey locust	0.3 × 0.3	4.0b	333	150	105	45	168	6.7b	87a
	Silver maple	0.3 × 0.3	4.3b	198	121	105	42	181	7.8b	33b
	Siberian. elm	0.3 × 0.3	4.5b	204	180	204	166	376	16.9a	76a

[a] Means within a column followed by the same letter do not differ significantly.

Table 2
Annual oven-dry yield and survival in close-spacing trial (1971) with two-year cutting cycle (study 3)

Species	Space[a]	Harvest period					Fifth harvest	
		First[b]	Second	Third	Fourth	Fifth	Yield[b]	Survival[b]
		(Mg ha^{-1})	(Percentage of first cut yield)				(Mg ha^{-1})	(%)
Boxelder	1	2.2	277	305	305	223	4.9	48
	2	0.9	510	600	544	578	5.2	75
	3	1.1	345	445	427	391	4.3	80
	Mean	1.4c	377	450	425	397	4.8a	68a
Catalpa	3	7.2	143	204[c]	Discontinued			
	Mean	7.2	143	204				
Siouxland Cottonwood	1	7.2	88	30	Abandoned due to high mortality			
	2	6.3	101	32				
	3	6.7	110	33				
	Mean	6.7a	100	32	–	–	–	–
Cottonwood	1	4.5	173	169	153	120	5.1	16
	2	6.1	139	133	133	80	4.9	27
	3	4.7	191	181	166	134	6.3	41
	Mean	5.1ab	168	161	151	111	5.4a	28c
European Black alder	1	5.2	215	142	65	65	3.3	32
	2	5.8	209	140	74	84	5.0	57
	3	4.3	167	151	58	79	3.5	77
	Mean	5.1ab	197	144	66	76	3.9a	55b
Silver maple	1	6.3	149	146	121	86	5.4	34
	2	5.3	198	187	143	92	4.9	54
	3	3.1	310	297	216	187	5.8	75
	Mean	4.9b	219	210	160	122	5.4a	54b
Sandbar willow	1	6.3	163	71	Abandoned due to high mortality			
	2	6.3	129	57				
	3	3.6	150	81				
	Mean	5.4ab	147	70	–	–	–	–
Sycamore	1	5.2	150	49	Abandoned due to high mortality			
	2	3.6	161	61				
	3	4.7	134	53				
	Mean	4.5b	148	54	–	–	–	–

[a] Code: 1–0.3 by 1.2 m, 2–0.6 by 1.2 m, and 3–1.2 by 1.2 m.

[b] Species means within a column followed by the same letter do not differ significantly. Spacing values not statistically evaluated, only shown to indicate trend.

[c] Three-year cycle.

had the best survival rate, and cottonwood had the worst (Table 2).

The first harvest yield (first two years) was significantly different (1% level) for species (Table 2). Siouxland cottonwood yield was the greatest and boxelder the least of all species. After three cuts, Siouxland deteriorated, while the field cottonwood increased its yield. Substantial differences in tree characteristics and biomass production with *Populus* clones were found between clones in Washington [16,17].

The yield at the closest spacings for all species combined was 31% greater than at wider spacings and was significantly different (1%) at two years; the yield differences moderated after each cut. At the third cut, the yield differences due to spacing were reduced to 11%. Thus, biomass yield was nearly the same for all three planting densities, showing no significant difference after four harvests (Table 2). The first coppice harvest yield was 57% greater than the first harvest for all species combined. Subsequent yields of the two maple species and the common cottonwood species were 64% and 45% greater, respectively, than the first cut. Silver maple and boxelder responded well to multiple cuttings. Annual coppice yields ranged from 4 to 12 dry Mg ha^{-1}, varying with precipitation fluctuations. Coppice and willow stands have been reported to achieve high yields at early dense spacing, while wider spacing tends to catch up later [18,19].

3.3. Conventional-spacing trials

Survival of all species was high (>80%) after the first cut, but decreased with each succeeding harvest. The mean survival of cottonwood for all spacings was especially affected by numerous cuttings, dropping from 83 to 44 to 28 and, finally, to 12% survival after 20 years. The reduction was much greater in the higher density planting. Survival of both black locust and silver maple remained high, with about 55% survival after four cuts (Table 3), but reduced the greatest at the closest spacing of 1.2 × 1.2 m.

The five-year first cut annual yields were 9.9 (cottonwood), 11.0 (locust), and 7.4 (maple) dry Mg ha^{-1} at the average spacing of 1.8 × 1.8 m. Three subsequent harvests at five-year intervals showed remarkably consistent growth over time. Oven-dry weight yields remained high after four cuts (Table 3); cottonwood annual yield decreased by more than 50%, whereas locust decreased by about 20%, and silver maple remained nearly the same as the first cut. The greater size of the cottonwood trees accounts for the relatively high yield.

Silver maple had nearly twice as many sprouts as locust or cottonwood (Table 3). The site was nearly completely used, showing little reduction in yield. Both black locust and silver maple showed little effect of multiple cuts.

At five years, total biomass yield of all three species combined at the closest spacing (1.2 × 1.2 m) was 1.5 times greater than at the widest spacing (2.6 × 2.6 m). At 10, 15, and 20 years it was only 0.5 times as large. Survival was greatly reduced in the closest spacing. At 20 years survival decreased allowing only general spacing comparisons as shown above.

The maximum size–density relationship of the mean tree weights in all three studies for silver maple indicates these stands have not yet begun to suffer mortality from crowding. Standing biomass at three years may be approaching the point of maximum growth at the wood-grass densities, those at the wider spacings are not. Two years does not appear to be the appropriate rotation age for the densities of 6700–26,900 trees ha^{-1}. Neither does five years for the conventional planting densities of 1500–7000 trees ha^{-1}. Self-thinning is occurring in the high-density plots and the individual tree size is increasing. Pure coniferous stands show a full stocking condition that follows the $\frac{3}{2}$ self-thinning law [4,5].

Table 3
Survival, number of stump sprouts, and oven-dry annual yield by species in conventional-spacing trials (1980) with five-year cutting cycles (study 4)

Harvest cycle	Species		
	Black locust	Cottonwood	Silver maple
First harvest at 5 years			
Survival (%)	92a	83a	97a
Yield (Mg ha^{-1})	11.0a	9.9a	7.4b
Second harvest at 10 years			
Survival (%)	73a	44b	79a
Sprouts	2.8b	2.5b	5.6a
Yield (Mg ha^{-1})	9.1a	7.2b	7.4b
Third harvest at 15 years			
Survival (%)	67a	28b	64a
Sprouts	3.4b	2.9b	4.4a
Yield (Mg ha^{-1})	8.6a	7.6a	5.0b
Fourth harvest at 20 years			
Survival (%)	58a	12b	54a
Sprouts	3.2b	3.1b	6.1a
Yield (Mg ha^{-1})	8.6a	4.6b	7.9a

[a] Means within a row followed by the same letter do not differ significantly.

4. Summary and conclusions

Biomass production in high-density (wood-grass) plantings result in a higher yield at the closest spacings (0.3 × 0.3 m) than the wider spacings (0.6 × 0.6 m) during the first few years of growth, but eventually produce the same biomass in later years. Siberian elm yield is at least 35% greater than the other species tested. Survival decreases substantially at all spacing distances with numerous cuttings cycles. Survival was high at 75% after six cuts for only honey locust and Siberian elm. The high cost associated with very dense planting regimes should be evaluated to determine the economic validity of high-density plantings.

Size and quantity of stump sprouts are important for harvesting efficiency. Fewer are considered beneficial. The number of sprouts and size of the stump was evaluated after the second cut. The number of major sprouts increased with spacing. Diameter of the largest sprout was the same for the two cottonwood sources and silver maple, and nearly 60% larger than the other species. The widest spacing yielded twice as many sprouts as the closest spacing and cottonwood produced 50% fewer sprouts than the seven-species average while silver maple produced 25% more. Secondary sprouts in maple were much smaller in size.

At wider spacings (0.3 × 1.2 to 1.2 × 1.2 m) and two-year cutting cycles, the yield was about 50% of the wood-grass (0.3 × 0.3 to 0.6 × 0.6 m) planting arrangement (see above). Survival remained high for boxelder (nearly 70%) but was only 50–70% for the other species. European black alder was severely damaged by winter sun scald. Boxelder, black locust, cottonwood, honey locust, silver maple, and Siberian elm can be cut as many as four times without a reduction in yield.

In the conventional spacing study having longer cutting cycles (five years), silver maple biomass yield was the same as or 40% less than found in the wood-grass studies and 40% less than the close spacing arrangement. After 20 years and four harvests yield remained relatively stable except for cottonwood which dropped 50% of the first cut. Cottonwood yield remains relatively high with fewer, but larger, trees.

Multiple harvests are feasible for many of the broad-leafed species compared in these studies. Survival decreases dramatically at the very close (less than 1 m) spacings. Tonnage remains high for cutting cycles of one, two, or five years. At least three harvests appear feasible. As plantings mature, survival decreases, individual tree size increases, and plot yield equilibrates among the spacing differences.

Considering high establishment costs along with survival results, a conventional spacing distance of about 2 m is suggested for high biomass production especially if plantation longevity of 10 or more years is desired.

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